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**Development of a Modelocked Ti:Al<sub>2</sub>O<sub>3</sub> Laser**

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**Concord, MA 01742**

**Contract #F49620-89-C-0089**

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## **1. Introduction and Summary of the Phase I Effort.**

Tunable lasers have become an important research instrument in two main areas of scientific investigation. One is in high-resolution spectroscopy, both linear and non-linear. The other is in the study of ultrafast phenomena, where the large gain-bandwidths associated with tunable devices have permitted direct, mode-locked generation of pulses shorter than 100 femtoseconds. Indirect generation of several-femtosecond pulses by external pulse compression techniques has also been achieved. Ultrashort pulses, besides making possible the examination of dynamics of processes in time regions never explored before, have practical applications to the study and characterization of high-speed electronic integrated circuits [1,2] and various components for high-speed electro-optic systems.

The ion-laser-pumped CW dye laser is perhaps the most widely used tunable system in scientific laboratories and is employed in both spectroscopy and ultrashort pulse generation. CW dye lasers have certain limitations, however. One is the tendency of the dye molecules to thermally or photochemically dissociate, thus requiring replacement of the dye solution. Near-infrared dye lasers are particularly troublesome to operate because thermal decomposition rates increase rapidly for molecular structures having near-infrared electronic transitions. The near-infrared region from 700-950 nm is of interest to the study of GaAs and other III-V semiconductor materials and devices. Another problem with dye lasers is perturbation of the optical cavity caused by fluctuations in the flowing dye stream. The perturbation translates into frequency jitter in the output of narrow-linewidth dye lasers and to instabilities in the operation of mode-locked lasers.

The discovery and development of tunable lasers based on the Ti:Al<sub>2</sub>O<sub>3</sub> crystal [3] has made it possible to replace the dye laser with a solid state system for applications requiring near-infrared wavelengths. With the use of frequency-doubling techniques, one can also employ the Ti:Al<sub>2</sub>O<sub>3</sub> laser as a source in the blue-green region, where dye operation is made difficult by both dye lifetime problems and the limited efficiency of cw pump lasers. In general, solid-state laser media eliminate the dye-laser problems discussed above. They offer unlimited shelf and operational lifetimes, without the need for dye flow systems, and do not suffer from the fluctuations associated with the dye stream.

The gain-bandwidth of the Ti:Al<sub>2</sub>O<sub>3</sub> system is actually broader than that of dye lasers, and thus mode-locked generation of ultrashort pulses comparable to or shorter than dye-laser systems is theoretically possible. Unfortunately, the characteristics of the Ti:Al<sub>2</sub>O<sub>3</sub> system are sufficiently different from dye lasers such that some of the mode-locking devices previously developed for ultrashort pulse generation from dyes cannot be used with Ti:Al<sub>2</sub>O<sub>3</sub> lasers. The

work proposed for this Phase I investigation was to evaluate innovative techniques for generation of ultrashort pulses from the CW Ti:Al<sub>2</sub>O<sub>3</sub> laser, with a long-term goal of developing and marketing a commercial scientific instrument. The techniques under consideration involved the use of controlled feedback into the laser cavity to narrow the pulselwidth of a conventionally mode-locked laser. Feedback would be from nonlinear reflectors based on the use of semiconductor materials.

At the time the present work was proposed Ti:Al<sub>2</sub>O<sub>3</sub> had been operated as an optically pumped cw laser in both the single-frequency [3] and modelocked [4] regimes. Modelocked operation via synchronous pumping [4] generated pulses with durations of 300 ps. Modelocked operation via loss modulation [4] provided improved performance with pulse durations of 95 ps and average output powers of 30 mW at a pulse rate of approximately 140 MHz. Since the proposal was written, several groups applied the technique of additive pulse modelocking (APM) to Ti:Al<sub>2</sub>O<sub>3</sub>, which resulted in the generation of 2-ps [5] and 600-fs-duration [6] pulses in Ti:Al<sub>2</sub>O<sub>3</sub>. Also, loss modulation with a high-efficiency, high-frequency, Brewster-angled AO-modulator [7] showed pulse durations as low as 6 ps, but the pulses were not transform-limited.

Our original work plan was changed to include a survey of the APM technique, with visits to research groups at the Massachusetts Institute of Technology, Imperial College of Science, Technology and Medicine (I.C.), and the University of St. Andrews. The performance of the I.C. laser demonstrates that a fiber-based APM Ti:Al<sub>2</sub>O<sub>3</sub> system is capable of generating transform limited subpicosecond pulses with low-dispersion fiber. A stabilization control loop built at St. Andrews demonstrated the feasibility of long term stabilization of such a laser.

Although the APM technique works well with Ti:Al<sub>2</sub>O<sub>3</sub> in a controlled laboratory environment it places demanding requirements on the optomechanical stability of the laser structure. In addition, the maintenance of subpicosecond-pulse generation with freedom from substantial resonator realignment has not been demonstrated over a broad tuning range. All the groups we visited considered that the APM Ti:Al<sub>2</sub>O<sub>3</sub> laser would be a difficult device to develop beyond the research laboratory, despite the fact that their own lasers performed well. The major concern expressed was that the fiber-based APM systems may be too complex to be reliable. Even though the APM technique might be worthy of study in a Phase II effort, we felt that the original experimental research plan, to investigate the use of semiconductor nonlinear reflectors for Ti:Al<sub>2</sub>O<sub>3</sub> mode-locked systems, was still appropriate.

The major part of our Phase I experimental effort was spent assembling an acousto-optically modelocked (AOM) Ti:Al<sub>2</sub>O<sub>3</sub> laser, a pulse autocorrelator and high-speed diagnostic electronics. We obtained pulses of 300-ps duration (estimated from an avalanche photodiode and sampling oscilloscope) from 760 nm to 880 nm and with pulse energies up to 4.6 nJ.

Our investigation into semiconductor nonlinear reflectors led us to conclude that:

- 1) "Hot" free-carrier-enhanced reflectivities require pulse durations of less than 10 ps.
- 2) Thermalized free-carrier induced changes can be used to enhance reflectivity in a Brewster-angled geometry and would require pulse durations less than the recombination time (100 ps-several ns) of the semiconductor material.
- 3) Two-photon-pumped semiconductor materials could be used to obtain an emission signal that is indicative of pulse duration and is sufficiently shifted from the laser wavelength to be easily observed.

Despite the limited time and funding available at the Phase I level we have gained sufficient insight into the mechanisms of semiconductor nonlinear reflection to conclude that these mechanisms offer significant promise for pulse compression and are worthy of continued investigation in a Phase II program.

## **2. Phase I Research Objectives.**

The specific objectives of the Phase I effort, as stated in the original Phase I proposal, were to:

1. Assemble and characterize the performance of a CW AOM Ti:Al<sub>2</sub>O<sub>3</sub> laser.
2. Investigate the effect of optical feedback from a nonlinear reflector on the performance of a CW AOM Ti:Al<sub>2</sub>O<sub>3</sub> laser.

With the discovery that APM techniques could be applied to the laser we added the following task:

3. Survey the efforts to develop APM Ti:Al<sub>2</sub>O<sub>3</sub> lasers.

The results of the Phase I effort are described in detail in the following Sections.

## **3. Phase I Research Effort.**

### **3.1 AOM Ti:Al<sub>2</sub>O<sub>3</sub> laser development.**

The major part of the Phase I effort was the assembly and characterization of a CW pumped, AOM Ti:Al<sub>2</sub>O<sub>3</sub> laser. A CW Ti:Al<sub>2</sub>O<sub>3</sub> laser has been developed as a commercial product at Schwartz Electro-Optics (SEO) and may be operated as either a linear or a ring resonator device by re-aligning two mirrors (M1 and M2 in Figure 1a). Key components from

the commercial laser were mounted on a 2' × 4' optical breadboard and a Brewster-angled AO-modulator prism was added to the laser cavity (see Figure 1b). This prism provides a means for tuning the Ti:Al<sub>2</sub>O<sub>3</sub> laser in addition to providing the loss modulation required for modelocking.

The AOM Ti:Al<sub>2</sub>O<sub>3</sub> laser was pumped with a 7 W CW argon-ion laser operating all-lines in the blue-green. The threshold pump power was 1.6 W for a nominal 5% output coupling loss. The average output power at 820 nm was approximately 380 mW for the 7 W of pump power (at the ion-laser, not absorbed pump power); the tuning curve is shown in Figure 2. The wavelength was measured with a Burleigh Wavemeter Jr and the laser pulses were monitored with the combination of an avalanche photodiode (APD) and sampling oscilloscope. The pulses were observed to be approximately 300 ps in duration over the 760 nm to 860 nm region. Our wavelength tuning range was limited by increased mirror losses and a breaking up of the modelocked pulses.

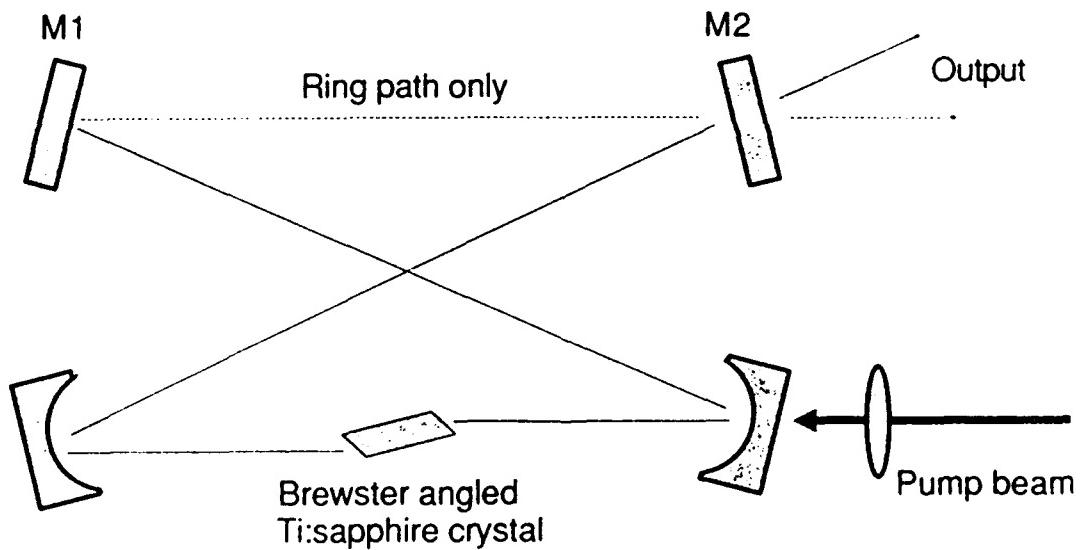
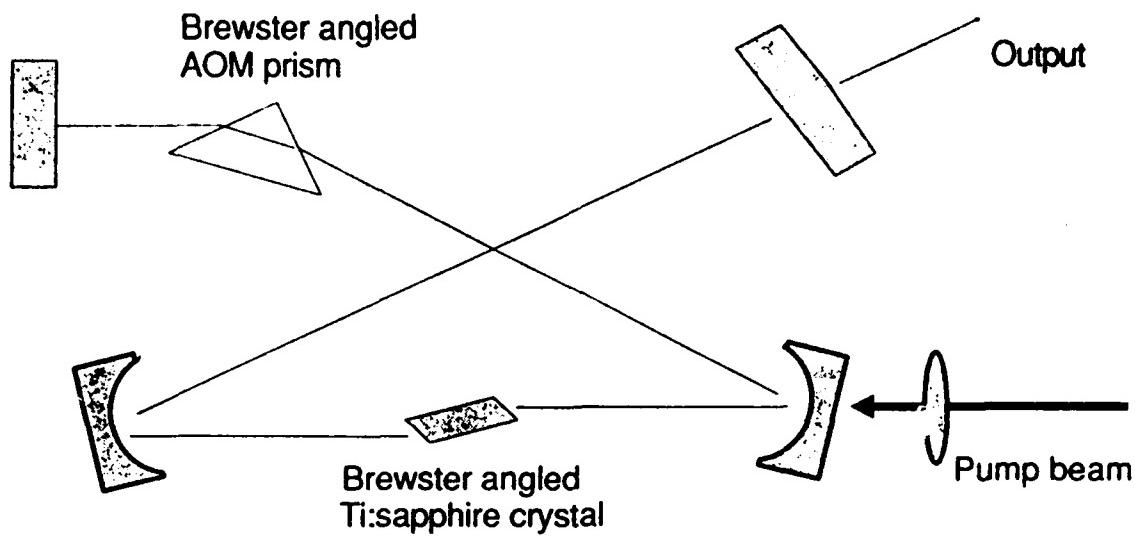
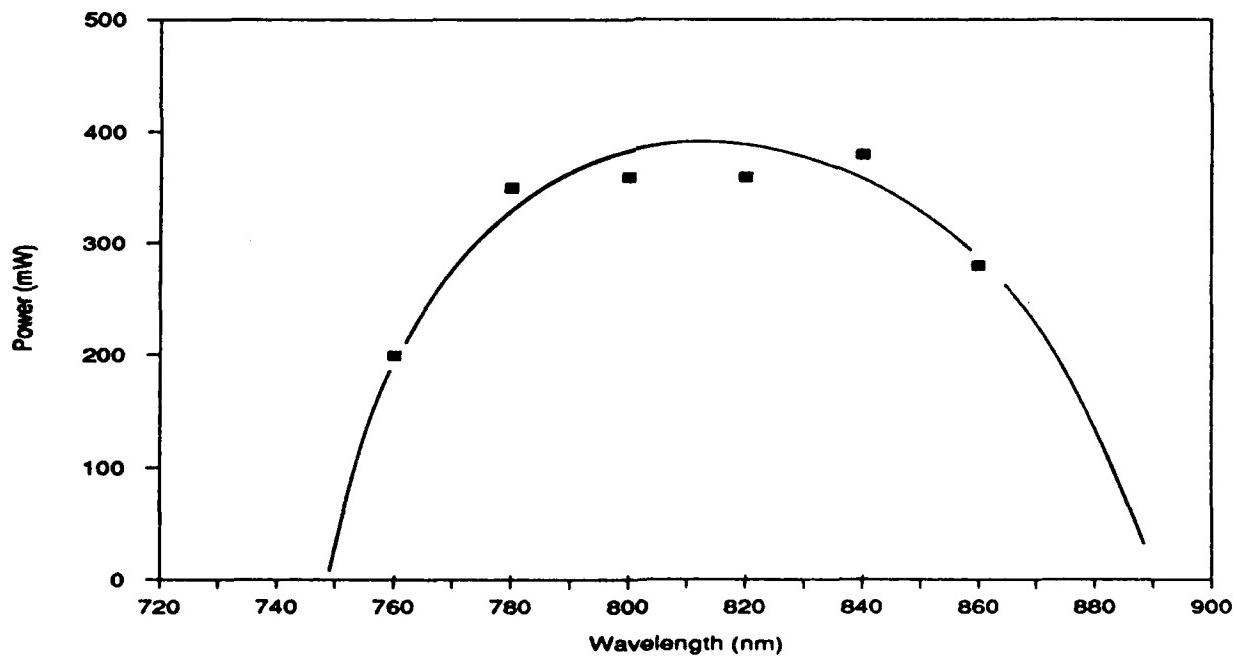


Figure 1a. CW Ti:Al<sub>2</sub>O<sub>3</sub> laser resonator.



**Figure 1b.** AOM Ti: $\text{Al}_2\text{O}_3$  laser resonator.



**Figure 2.** AOM Ti: $\text{Al}_2\text{O}_3$  laser tuning curve for 7 W of pump power.

Optimum-duration pulses are generated when the round-trip rate of the resonator matches the loss modulation rate of the AO-modulator. We controlled the exact resonator length by placing the output-coupler on a precision translation stage and adjusting the stage while monitoring the pulses with the APD and sampling oscilloscope.

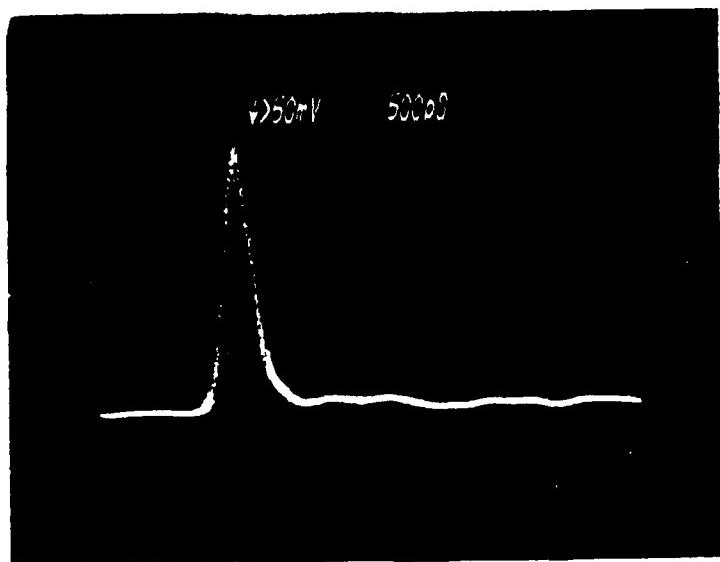
The AOM was designed for use in argon-ion lasers and is typically driven by RF at 41 MHz. Our prism was driven by the combination of high-stability, high-spectral-purity, voltage controlled oscillator and a 1-W power amplifier. Initially, we impedance-matched the transducer of the modulator to the output of the oscillator/amplifier at 123 MHz, the third harmonic of the transducer resonance frequency, in order to optimize our pulse durations by reducing the effective aperture time of the modulation (see Equation 36a, ref[8]). Unfortunately, the acoustic loss coefficient in fused silica (the prism material) increases rapidly above 100 MHz thereby reducing the "Q" of the acoustic resonator and the modulation efficiency. This effect reduced the single-pass modulation depth to approximately 1%, which offset the advantage of operation at the third harmonic. Typical pulse durations were estimated at 350 ps from sampling-oscilloscope data.

We then changed the AO-modulator impedance matching and drive frequency to the fundamental and obtained a single-pass modulation depth of approximately 10% for 1 W of RF drive. Initially we still obtained the same duration pulses as earlier. At this point we observed deep modulation in the laser spectrum when it was displayed with an optical spectrum analyzer (8 GHz FSR, scanning Fabry-Perot etalon) and discovered that the high-reflectivity mirror behind the AO-modulator was mislabeled and had been placed in the resonator backwards, thereby forming an intracavity etalon. When we reversed the mirror the spectral modulation disappeared and the pulse duration decreased to 300 ps.

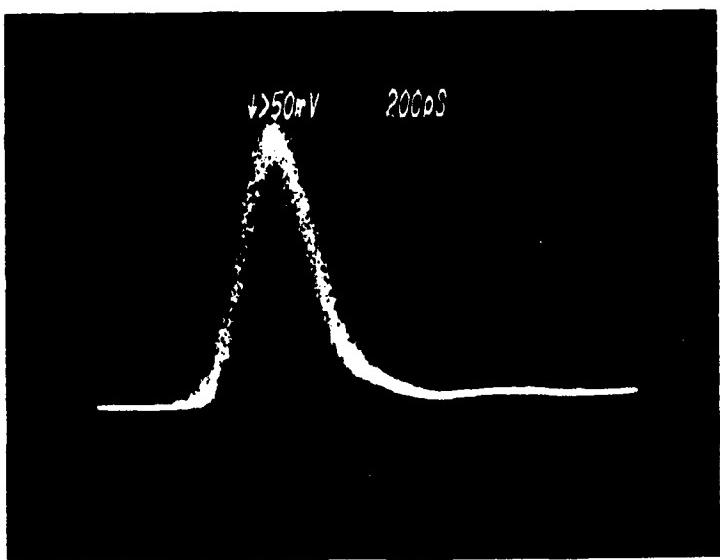
Typical laser pulses are shown in Figures 3(a) and (b). The oscillograms shown are the convolution of the laser pulses, avalanche photodiode response, and the sampling oscilloscope response. Both the laser pulses and the APD response are an order of magnitude greater than the oscilloscope response, so for Gaussian pulses:

$$\tau_{\text{meas}} = (\tau_p^2 + \tau_{\text{APD}}^2)^{1/2}$$

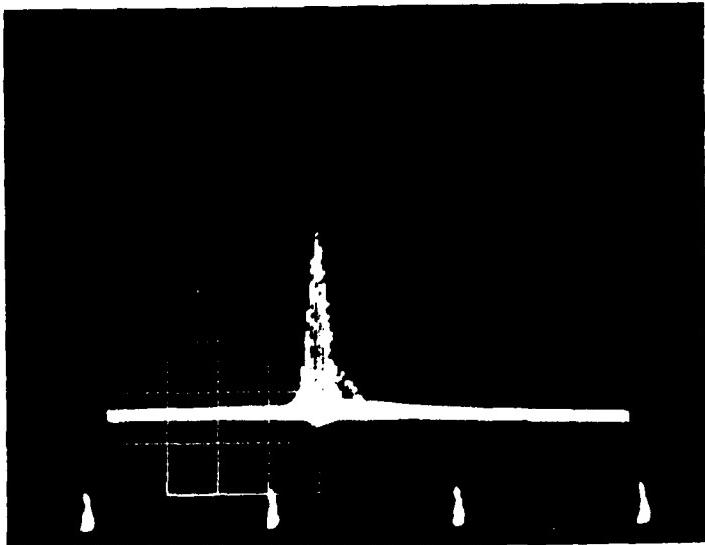
Our APD (BPW 28, ref [9]) had a 180 ps response and our estimated laser pulse duration was 300 ps.



**Figure 3a.** AOM Ti:Al<sub>2</sub>O<sub>3</sub> laser pulse.



**Figure 3b.** AOM Ti:Al<sub>2</sub>O<sub>3</sub> laser pulse. Scale expended to 200 ps/div.



**Figure 4.** AOM Ti:Al<sub>2</sub>O<sub>3</sub> laser spectrum centered at 818 nm. Scale is 3.1 nm/div.

We measured the laser spectrum with a 0.64-m grating spectrometer, setup with a 1200 grooves/mm grating and with a Si-photodiode detector array mounted in the exit plane. The spectrum width was 1.5-nm FWHM as shown in Figure 4. Hence, the time-bandwidth product for the laser output was approximately 210, or 480 times larger than the Fourier-transform limit for Gaussian pulses.

The prism-tuning arrangement allows broadband operation of many groups of longitudinal-modes such that these groups may be modelocked independently. The elimination of the prism by, say, using a Brewster-angled AO-modulator would allow us to add birefringent tuning elements to reduce the bandwidth to a single group of modes. Improvements in the modulation frequency and depth using a high-efficiency, high-frequency, Brewster-angled AO-modulator should then lead to the generation of shorter pulses. In addition we would have to improve the modulation-depth stability with an electronic feedback system that locks the acoustic resonance frequency of the modulator to that of the oscillator [10].

The standard technique for measuring the duration of modelocked laser pulses is the second-order autocorrelation of temporally overlapping pulses by the nonlinear mixing process of second-harmonic generation [11]. This technique is usually implemented using a modified

Michelson interferometer to provide two pulse trains with an adjustable time delay between them. Subsequent mixing of these pulses in a nonlinear-crystal to generate the second-harmonic yields the second-order autocorrelation function of the pulse intensity profile.

We assembled a scanning autocorrelator based on a motor-driven cam system to provide a real-time pulse duration measurement system with 100 ps scan range. The autocorrelator was designed to provide information about the spectral-chirp in the pulse by displaying interferometrically resolved data [12].

We were able to use the autocorrelator to observe both the 3:1 contrast ratio [11] in the mean second-harmonic signal and the 8:1 fringe-resolved signal [12] for overlapping pulses compared to the sum of the background signal for the individual paths of the interferometer. A slight roll-off in the second-harmonic signal, consistent with 300 ps FWHM Gaussian pulses, was observed at the maximum scan range of the autocorrelator. We were unable to observe the complete autocorrelation because the scan range of the autocorrelator was less than the pulse duration.

### 3.2 Nonlinear reflector investigation.

The AOM Ti:Al<sub>2</sub>O<sub>3</sub> laser is a broad-bandwidth system capable of utilizing the complete tuning range available from the gain medium without restriction by the AOM. Yet, the pulse durations are longer than would be required for many applications. The second part of the Phase I research plan addressed this problem with a preliminary investigation of a novel pulse-compression scheme that retains the broad-bandwidth operation of the laser.

Conventional methods for pulse compression fall into two categories, extra-cavity compression based on fiber/grating-pair schemes [13], and intracavity compression based on saturable absorbers [14]. Both techniques could be applied to the AOM modelocked Ti:Al<sub>2</sub>O<sub>3</sub> laser, but require careful matching of fiber or saturable-absorber characteristics to the laser wavelength of operation.

In the Phase I proposal we discussed a means of improving the performance of the modelocked TiAl<sub>2</sub>O<sub>3</sub> laser by introducing a nonlinear reflector into the loss-modulated CW modelocked laser. An analogy may be drawn between the use of a saturable absorber in hybrid-modelocking of dye lasers [14] and the use of a nonlinear reflector for the TiAl<sub>2</sub>O<sub>3</sub> laser. The saturable absorber is a nonlinear element with increasing transmission as a function of increasing incident intensity. Our proposed nonlinear reflector was a germanium optical flat, which would exhibit increasing reflectivity as a function of increasing incident intensity [15]. Both the saturable absorber and a nonlinear reflector are capable of providing pulse compression in a suitable resonator configuration with a gain medium. Improved durability and suitability for

photon energies above the germanium band-gap energy were advantages for the nonlinear reflector, which would provide us with a broad-bandwidth, intracavity pulse-compression element.

The AOM laser resonator was modified, as shown in Figure 5, to include a feedback path incorporating the germanium reflector. A 4% beamsplitter defines a resonator path with an output coupler to provide feedback for the normal AOM operation, and a second path to the nonlinear reflector. The optical path in these two arms was matched to ensure temporal overlap of the pulses. A focussing lens was included in the path to the germanium optical-flat to adjust the incident power density to obtain enhanced reflectivity during the modelocked pulse.

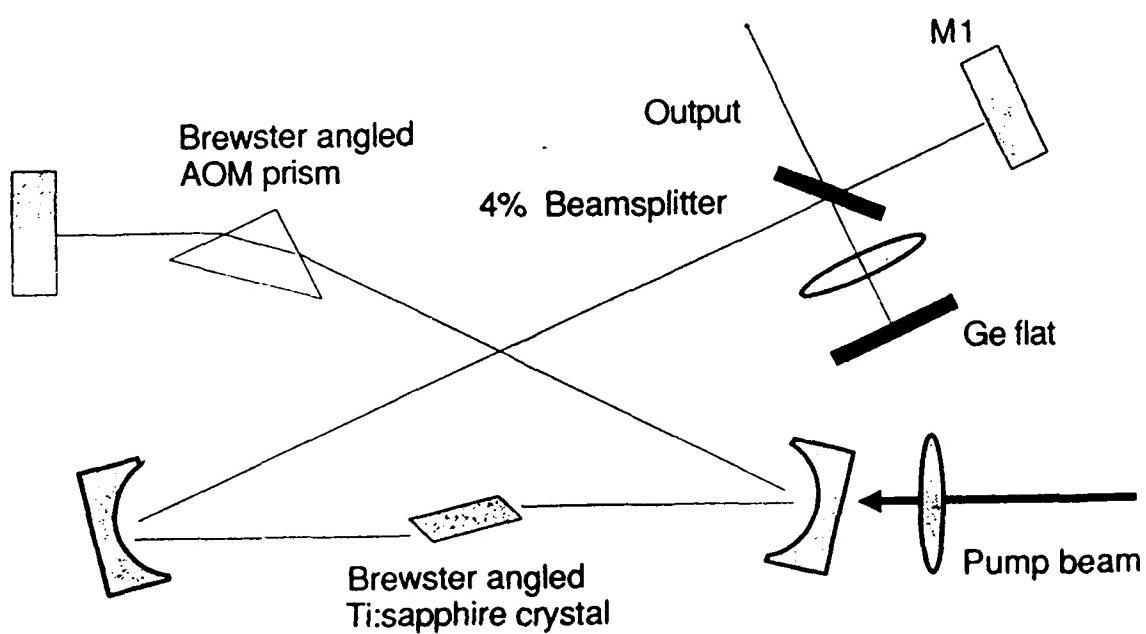


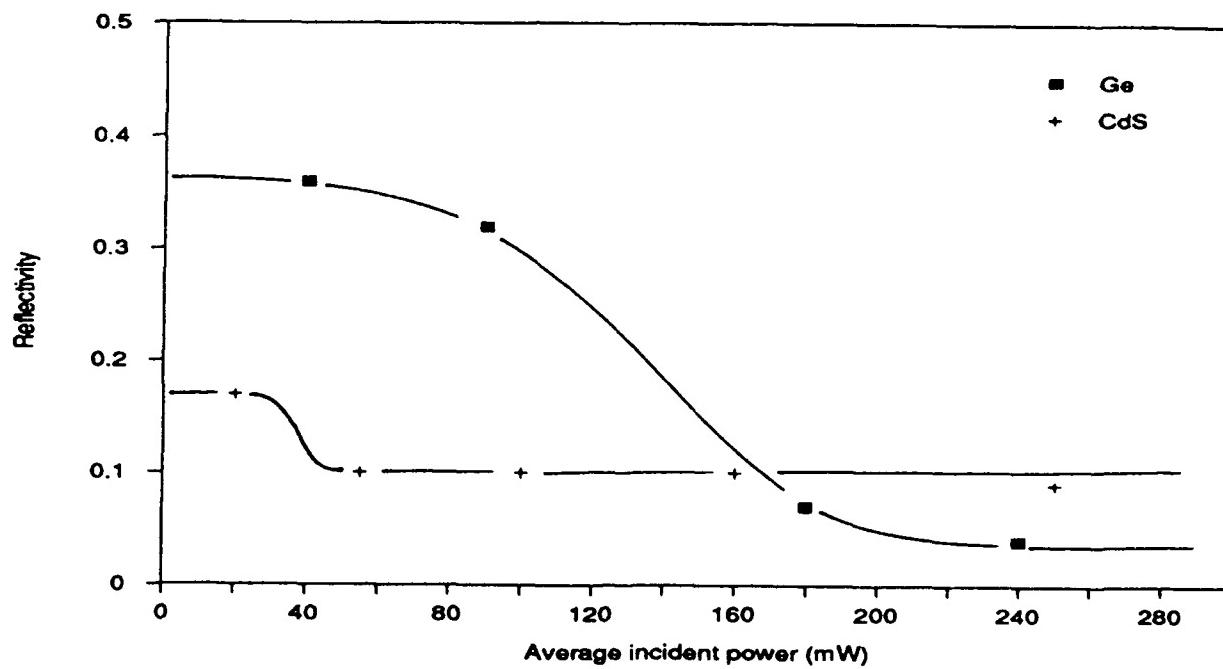
Figure 5. Hybrid AOM and nonlinear reflector Ti:Al<sub>2</sub>O<sub>3</sub>, resonator.

While operating the modified laser resonator we observed two types of effects. When the AOM pulses were very stable we frequently observed a break-up in pulse stability with the reflector in operation, with longer pulses being observed for mismatchs of the two resonator path lengths. When the AOM pulses were less stable we sometimes observed a stabilization of the pulse shape and amplitude but at the expense of duration. At first we thought both these effects were due to the linear 36% reflection from the Ge flat. However, with hindsight we may have been observing the effect of a negative nonlinear reflectivity for the case of pulse stabilization and broadening. We did not see evidence of an enhancement in reflectivity (ie. a positive nonlinear reflector) of the Ge.

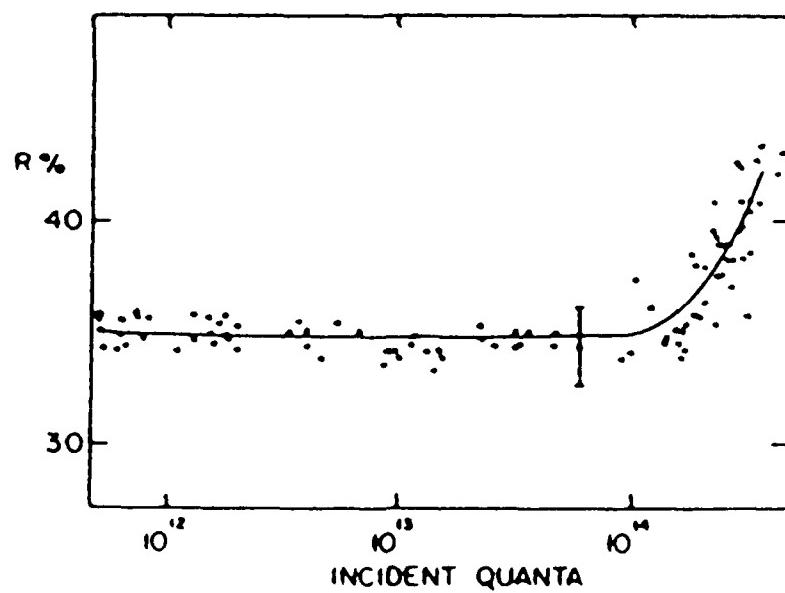
As a test of other possible nonlinear reflectors we tried polished pieces of CdS and ZnSe materials, for which two-photon generation of carriers would be possible. When the mode-locking modulator was on we observed green luminescence from the CdS crystal, a strong indication that two-photon-induced carriers were present. However, with neither material did we see evidence of reflectivity enhancements.

Our support for the presence of negative nonlinear reflectivity is shown in Figure 6. Towards the end of the Phase I effort we measured the proportion of incident power reflected from the Ge flat as a function of average incident power. The focussing lens was still in use and the maximum peak-power density was approximately  $16 \text{ MW cm}^{-2}$ . Data is also shown for cadmium sulfide (CdS). Both materials show a decrease in reflectivity at higher incident powers that is characteristic of thermalized-carrier populations in semiconductor materials [16]. This was not what we had expected based on our earlier research of the literature.

Figure 7, from [15], shows experimental data on the enhanced reflectivity of germanium at incident quanta of up to  $10^{15}$  corresponding to an optically generated carrier density of approximately  $10^{20} \text{ cm}^3$ . At our modelocked pulse-rate of 82 MHz there will be approximately 3.7 nJ ( $1.4 \times 10^{10}$  quanta at 820 nm) of intracavity energy/pulse incident on the germanium optical flat. The required carrier density of  $10^{20} \text{ cm}^3$  could be achieved by focussing the intracavity beam to a  $15 \mu\text{m}$  spot size, assuming a  $1 \mu\text{m}$  penetration depth. This estimate assumes that the transient changes in reflectivity persist for the duration of the laser pulse and are the result of an accumulation of optically induced carriers.



**Figure 6.** Average reflectivity of Ge and CdS as a function average incident power of 820 nm laser pulses from the AOM Ti:Al<sub>2</sub>O<sub>3</sub> laser.



**Figure 7.** Reflectivity of Ge at room temperature as a function of 1.06  $\mu\text{m}$  incident laser pulse energy. (Taken from ref. [8])

Yet, the observation [15] of enhanced reflectivity, in contrast to the more typical reduced reflectivity [16], requires the generation of hot-carriers which thermalize within 10 ps [15]. So, to generate an enhanced reflectivity the peak-power density at the germanium should be approximately  $210 \text{ MWcm}^{-2}$ . The peak-power density attained with our present AOM Ti: $\text{Al}_2\text{O}_3$  laser focussed to a  $10 \mu\text{m}$  spot-size with a 7-mm focal length, F1.1 diode laser collimation lens was only  $16 \text{ MWcm}^{-2}$ . Hence, we should only observe a reduction in reflectivity and not enhancement.

The reflectivity reduction is due to the reduction of effective refractive index through the generation of free-carriers. We can convert this index reduction into an increase in reflectivity by orienting the semiconductor element at Brewsters' angle for its' nominal index prior to laser irradiation. Any optical element at Brewsters' angle will appear to increase in reflectivity for any (positive or negative) changes in refractive index. This is illustrated in Figure 8, where the normal incidence and Brewster angle reflectivities of Ge are plotted for a refractive index change of up to 50%. So, by the use of the Brewster-angled focussing geometry shown in Figure 9 we should be able to use the slower thermalized free-carrier index changes to provide a positive nonlinear reflection device.

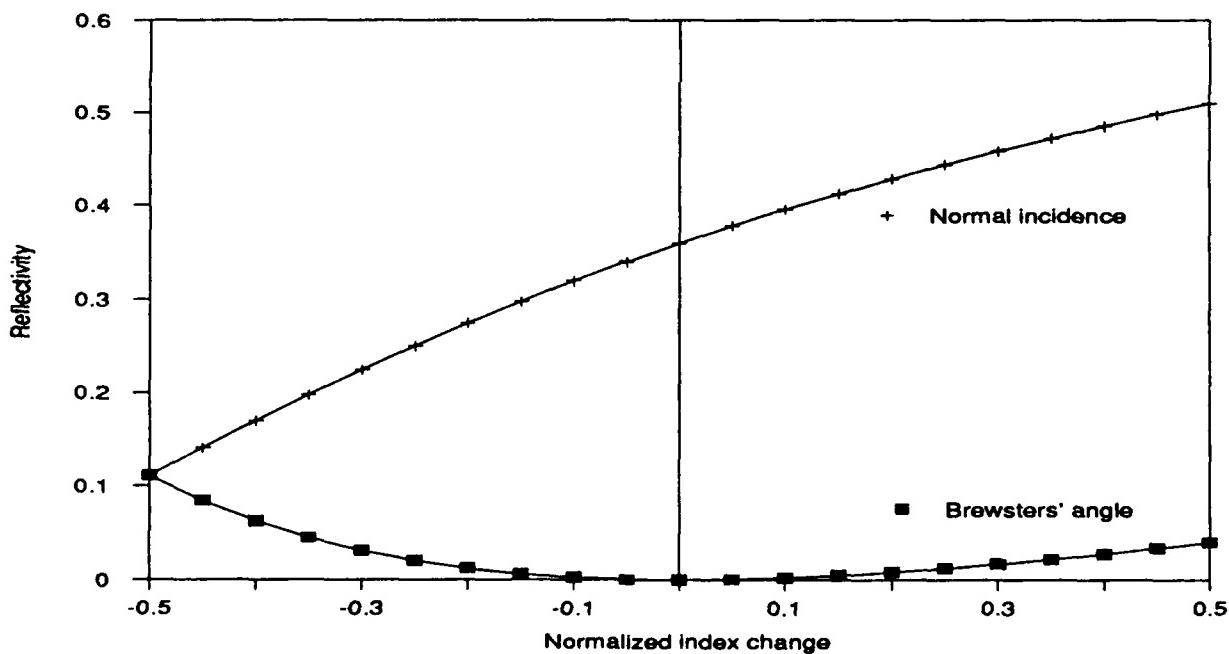
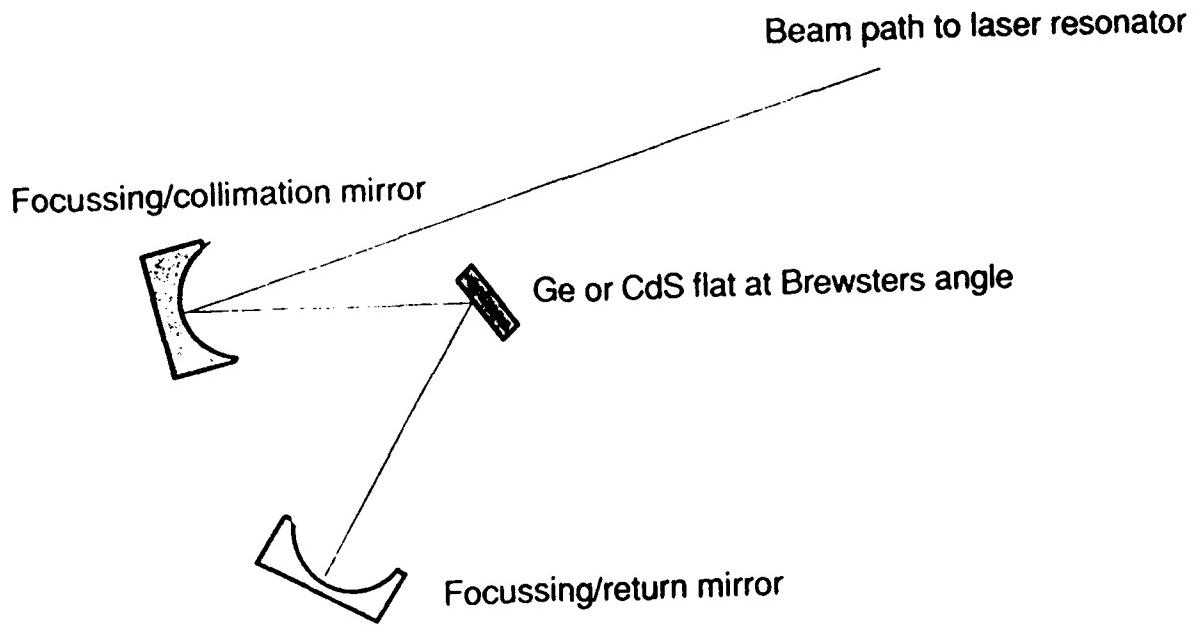


Figure 8. Normal incidence and Brewster angle reflectivities for refractive index changes.



**Figure 9.** Brewster-angled optical geometry for the nonlinear reflector.

In addition, we can use CdS as our nonlinear reflector and benefit from the fact that green light is generated when the free-carriers recombine. The recombination emission can be used as an indicator of the modelocked pulse durations because the free-carriers are generated by two-photon absorption (analogous to the second-harmonic generation used in the autocorrelator) which increases with peak-power.

The conclusions we have reached from our preliminary study of nonlinear reflectors are:

- 1) "Hot" free-carrier enhanced reflectivities require pulse durations of less than 10 ps.
- 2) Thermalized free-carrier-induced changes can be used to enhance reflectivity in a Brewster-angled geometry and would only require pulse durations less than the recombination time (100 ps-several ns) of the semiconductor material.
- 3) Two-photon-pumped materials can be used to obtain an emission signal that is indicative of pulse duration and is sufficiently shifted from the laser wavelength to be easily observed.

Given the limited time and funding available at the Phase I level we have gained sufficient insight into the mechanisms of semiconductor based nonlinear reflection effects to conclude that these mechanisms offer significant promise for pulse compression and are worthy of continued investigation.

### **3.3 Survey of APM Ti:Al<sub>2</sub>O<sub>3</sub> lasers.**

#### **3.3.1 Introduction.**

Coupled-cavity modelocking (CCM) and additive-pulse modelocking (APM) are the respective UK and US acronyms for the technique of pulse shaping a portion of the output from a modelocked laser which is then fed back into the laser to promote shorter pulse generation [17,5,6]. Operation of an APM laser system does not rely on the soliton effects that have been used with F-center lasers in the near-infra-red [18], but does not exclude the use of soliton formation.

The APM laser is a relatively new phenomenon that is currently being applied to F-center lasers [17,19] and Ti:Al<sub>2</sub>O<sub>3</sub> lasers [5,6]. The full potential of the APM technique remains to be demonstrated at this stage. However, published data by Taylor et al. [6] and Goodberlet et al. [5] have demonstrated the generation of subpicosecond pulses in Ti:Al<sub>2</sub>O<sub>3</sub>.

As part of our Phase I investigation into modelocking of the Ti:Al<sub>2</sub>O<sub>3</sub> laser we reviewed the fiber-based APM technique currently in use by the other researchers. We will describe the APM and related work seen Massachusetts Institute of Technology (M.I.T.), Imperial College of Science, Technology, and Medicine (I.C.), and the University of St. Andrews (St. Andrews).

#### **3.3.2 Massachusetts Institute of Technology.**

The APM work on Ti:Al<sub>2</sub>O<sub>3</sub> at M.I.T. is being performed in Dr. J.G. Fujimoto's research group and is strongly related to a similar effort at M.I.T. on F-center lasers in Professor E.P. Ippen's research group. As with all the APM work to date there are strong historical links to the soliton work at both AT&T Bell Laboratories [18] and British Telecom [20].

The significant aspects of the work at M.I.T. are two-fold. On the experimental side, Fujimoto's group was the first to report on an APM system that did not require active modulation to start the modelocking process [5]. On the theoretical side, Ippen's group showed that the pulse shortening process in a fiber-based APM does not have to involve soliton formation [21].

In the majority of APM systems part of the laser output is fed into a second resonator containing a single-mode fiber, the output of this second resonator is fed back into the laser in synchronism with the intracavity mode-locked pulses so as to interferometrically interact. The laser output coupler is usually a common optical element to both resonators. The laser may self-start [5] from longitudinal mode beating or can be loss/gain modulated [17,6] to induce mode-locking. The pulse compression mechanism proposed by Ippen's group [21] is based on

self phase modulation effects in the fiber leading to intensity dependent phase delays in the second resonator. This will lead to changes in the interferometric addition of the original laser field and the second resonator field that will favor the generation of shorter duration pulses.

The successful implementation of a fiber-based APM laser is non-trivial and presents many problems for the laser engineer/physicist. Although the M.I.T. effort in Ti:Al<sub>2</sub>O<sub>3</sub> demonstrated a passive (ie. self-starting) APM laser their implementation of this system is not yet well behaved. On our visit to the laboratory at M.I.T. we observed that the mechanical design of the laser is not very rigid and is very sensitive to vibrational excitation through the optical table and acoustic coupling. This vibrational excitation manifests itself in misalignment of the fiber coupling optics and hence cessation of lasing (dropout) every few seconds. The use of an electrical feedback loop to match the two resonator lengths [22] did very little to help this situation directly, but indirectly helps by attempting to reset the cavity length mismatch to obtain stable output pulses until the next dropout occurs. However, these attributes are not fundamental flaws in the APM process and can be corrected through an improved opto-mechanical design.

Typical output pulses from the M.I.T. laser are 2-ps duration and chirped in wavelength to approximately 4-times the transform limit. Pulse compression to 560 fs was achieved with a pair of diffraction gratings after the laser. From our discussions with Fujimoto et al., their 2-ps chirped pulse appears to be a fundamental limit for their basic resonator/fiber combination due to positive dispersion in the fiber. The same effect has been observed at St. Andrews, while the use of a low dispersion fiber at I.C. led to the formation of transform-limited pulses of 650 fs duration [6] directly from the laser oscillator.

### 3.3.3 University of St Andrews.

The research group we visited at St. Andrews is run by Professor W. Sibbett and consists of one staff scientist, two postdoctoral research fellows and six graduate students. The group has concentrated their efforts in the areas of femtosecond pulse generation in dye lasers, and solid-state lasers. Their other major area is in nonlinear processes in fibers, diode pumped solid-state lasers, and streak camera technology.

The effort on Ti:Al<sub>2</sub>O<sub>3</sub> at St. Andrews was, at the time of our visit, a few months old and was based on APM of two commercially available Ti:Al<sub>2</sub>O<sub>3</sub> lasers, an SEO Titan CW-BB and a Spectra Physics laser. Only the Spectra Physics system had been converted to run as an APM laser during our stay. The performance was almost identical to that seen at M.I.T. However, the stability of their laser was much better than the M.I.T. laser.

The configuration was similar to those at M.I.T. [5] and I.C. [6] and used approximately 10 cm of single-mode (@830 nm) fused-silica fiber manufactured by the Andrew Corp. Fiber coupling was with Melles Griot diode laser lenses arranged to provide 20x imaging of the fiber output facet onto the high-reflector terminating the additive resonator. This imaging arrangement eliminated the mirror damage seen by the M.I.T. group using a butt-coupled high-reflector and was found to be more misalignment insensitive than the collimated output used by the group at I.C.

The overall mechanical design was very rigid and the laser ran without any dropouts for the 40 minutes we were in the laboratory. The pulses were displayed using a real-time interferometric autocorrelation [12] technique which showed direct evidence of the chirped nature of the output. The cavity length of the additive resonator was slaved to the master laser resonator with a sophisticated electro-mechanical control loop, controlling the position of the high-reflector. The control loop was based on the soliton laser stabilization scheme devised by Mollenauer [22]. An essential feature of this control loop was the ability to hold loop output during dropouts. While in the laboratory we induced a dropout by hitting the optical table and the control loop recovered the system within a couple of seconds. The equivalent test on the M.I.T. laser would usually extinguish the modelocking because the M.I.T. control loop would drive their piezo-fiber stretcher to the limit of the stretcher travel and would be unable to recover the correct operating position.

### **3.3.4 Imperial College of Science, Technology and Medicine.**

The research group I visited at I.C. is run by Professor J.R. Taylor and consists of two postdoctoral research fellows and nine graduate students. The group has concentrated their efforts in the areas of femtosecond pulse generation in dye lasers, solid-state lasers, and fiber lasers. Their other major interest is in nonlinear processes in fibers, including soliton physics. The effort on Ti:Al<sub>2</sub>O<sub>3</sub> modelocking at I.C. may be subdivided into three sections.

Their published work includes the fiber-based APM laser [6] generating 650-fs, transform-limited pulses. The major differences between this laser and the M.I.T. laser are the use of a polarization preserving fiber (made by York Corp.) with low dispersion at 780 nm and active modulation with an acousto-optic modulator to start the system. At a later date the same system was operated in the self-starting mode demonstrated at M.I.T. [5] and, once again, generated transform limited pulses of 650-fs duration. This laser also showed some evidence of mechanical instability, leading to periodic dropouts.

During the course of their investigation of the APM system the I.C. group found that increasing the bandwidth of the tuning element in the laser resonator did not lead to shorter pulse durations. Even the removal of the tuning element still only produced pulses of 600 fs. Taylor concluded that the Ti:Al<sub>2</sub>O<sub>3</sub> crystal was operating as a birefringent element [23] restricting the laser bandwidth.

Their second Ti:Al<sub>2</sub>O<sub>3</sub> effort is primarily theoretical [24] and is a computer modelling of the effects of linear and different nonlinear external resonators on the modelocked output of lasers operated in the APM regime. This work is funded by British Telecom and was originally confined to nonlinearities in fibers, but has grown into a more generic effort. The most interesting outcome of this work to date was the recent discovery that linear optical feedback with time-varying phase could modelock a laser in bursts analogous to the output from a Q-switched, modelocked system. An experimental investigation of this effect involved a single feedback mirror external to a CW Ti:Al<sub>2</sub>O<sub>3</sub> laser forming a second resonator of matching optical length. This mirror was then translated at constant velocity with a piezoelectric drive driven by a voltage ramp. The experimental results were as predicted by the theory. The mirror ramp rate and velocity influenced the Q-switch rate but the pulse durations were always approximately 40 ps [25]. This technique does not offer shorter durations as there is no nonlinear compression mechanism. Yet, the pulse durations are impressive for a technique that can be added to any CW Ti:Al<sub>2</sub>O<sub>3</sub> laser for an additional few hundred dollars in components. This physical process may also provide some insight into the self-starting mechanism for the fiber-based APM system.

The third Ti:Al<sub>2</sub>O<sub>3</sub> effort at I.C. involved passive modelocking with a conventional saturable absorber dye. This work is now complete and was not published as the results were only in the several picosecond range. The problem when passively modelocking a gain medium with a long upper-state lifetime (such as Ti:Al<sub>2</sub>O<sub>3</sub>) is that the pulse durations are limited by the recovery time of the saturable absorber [26].

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